# Stratified Flow in a Room with Displacement Ventilation and Wall-Mounted Air Terminal devices

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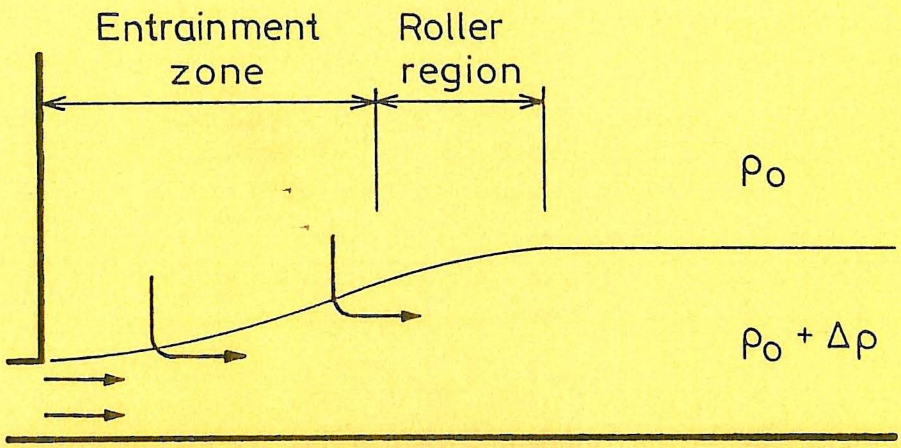


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# STRATIFIED FLOW IN A ROOM WITH DISPLACEMENT VENTILATION AND WALL-MOUNTED AIR TERMINAL DEVICES

**P.V. Nielsen, Ph.D.**
*Member ASHRAE*

## ABSTRACT

*This paper describes experiments with wall-mounted air terminal devices. The stratified flow in the room is analyzed, and the influence of stratification and the influence of room dimensions on the velocity level and on the length scale are proved. The velocity level in the occupied zone can be described by a single equation based partly on stratified flow theory and partly on measurements.*

*A radial stratified flow is obtained if the room is ventilated by a single diffuser or if the diffusers are placed some distance from each other.*

*A two-dimensional stratified flow is obtained if the room is ventilated by a number of diffusers placed close to each other on one sidewall. The velocity has a slight tendency to be constant in an area along the floor.*

## INTRODUCTION

For many years, ventilation systems with vertical displacement flow have been used in industrial areas with high thermal loads. Recently, vertical displacement flow systems have become popular for comfort ventilation in rooms with thermal loads, e.g., offices.

Air is supplied directly into the occupied zone at low velocity from wall-mounted diffusers. The plumes from hot surfaces, equipment, and people entrain air into the occupied zone and create a natural convective flow upward in the room (Figure 1).

Displacement flow systems have two advantages compared with traditional mixing systems:

- an efficient use of energy—it is possible to remove exhaust air from the room where the temperature is several degrees higher than the temperature in the occupied zone, which creates a higher air inlet temperature at the same load; and
- an appropriate distribution of contaminated air—the vertical temperature gradient (or stratification) implies that fresh air and contaminated air are separated and that the most contaminated air is found above the occupied zone.

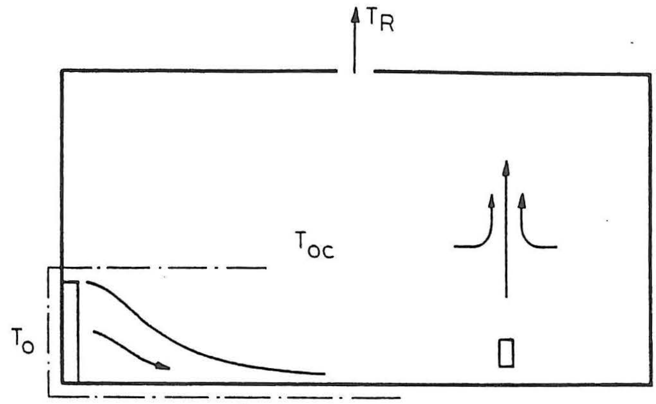


*Figure 1 Room with low-level diffuser, heat source, and displacement flow.*

It is important to examine the flow in front of an air terminal device and to investigate whether this flow can be treated separately from parameters such as room geometry, heat source location, location of exhaust opening, etc., as indicated in Figure 1. The design procedure is simplified if the flow depends only on certain parameters, such as type of diffuser, obstacles on the floor, flow rate, and Archimedes number.

The theories of both wall jet flow and stratified flow are used in discussing the measurements in this paper. The discussion is divided into two cases according to geometry and the number of diffusers. The first case is radial flow from a single diffuser in situations where the air movement is not influenced by the sidewalls. The second is flow from a number of diffusers placed close to each other on the end wall. The flow merges into a two-dimensional flow with a velocity characteristic different from that in radial flow.

Radial flow is characterized as flow close to the floor that has an virtual origin at the diffuser. Two-dimensional flow is characterized as plane flow at the floor, parallel to the sidewalls of the room.

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## ISOTHERMAL WALL JETS AND STRATIFIED FLOW THEORY

This section discusses two different models that may have some relevance to the actual flow in the vicinity of the floor.

The wall jet description is relevant to mixing ventilation (Nielsen 1991) and may also be relevant to the flow in rooms with displacement ventilation in cases where the temperature differences are very small because it shows the type of flow that may result when the heat load approaches zero.

Stratified flow is the type of flow generally relevant to displacement ventilation. The theory behind stratified flow is used in hydraulic models, such as models of water with density difference discharged into a pond; it has also been used to describe processes such as the Föhn winds in the atmosphere.

Stratified flow theory has recently been used in room air motion by Lane-Serff et al. (1987), Sandberg and Holmberg (1990), Sandberg and Mattsson (1991), and Nielsen (1992), for example.

## WALL JET MODEL

The flow from a low-velocity diffuser may contain some elements of wall jet flow in situations where the temperature difference is small. The height of the diffuser, $h$, is often fairly large compared to other dimensions in the room, which means that an initial flow region may cover a large part of the room.

The initial region of flow in front of the diffuser may be described as a "constant velocity core." The velocity in the core is obtained at the distance where all the small jets from the openings in the surface of the diffuser merge into a coherent flow. Figure 2 shows how a shear layer between this flow and the surrounding air volume reduces the constant velocity core with increasing distance. The maximum velocity in the initial region is constant when the flow is two- or three-dimensional, while the velocity is inversely proportional to the distance, $x$, when the flow from the diffuser is radial.

Two-dimensional or three-dimensional flow gives the relation

$$u_x \sim const, \tag{1}$$

and radial flow gives the relation

$$u_x \sim \frac{1}{x}. \tag{2}$$

Two-dimensional flow only takes place when the opening covers the entire width of the room or when a number of openings are located close to each other. Three-dimensional flow occurs when the velocity is perpendicular to the surface at the supply opening. Even a very small temperature difference changes a three-dimensional wall jet

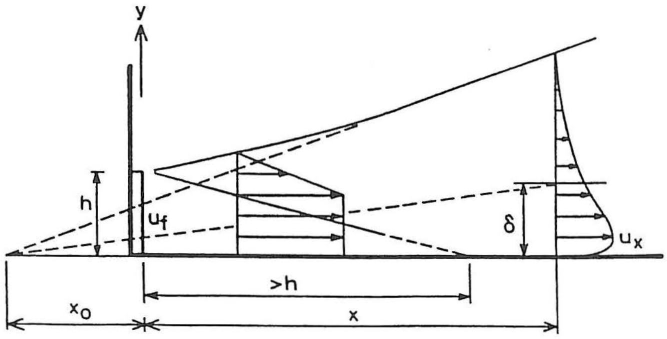


*Figure 2* *Idealized wall jet flow from an opening. The figure shows the initial flow region close to the opening and a fully developed flow in the right side of the figure.* $T_{oc} - T_o \sim 0.0$.

into radial stratified flow because the buoyancy effect accelerates the flow toward the floor and, therefore, introduces spreading of the flow field.

Radial flow at the diffuser is common and is generated by blades in the diffuser in such a way that the velocity obtains a radial distribution at the surface.

A wall jet flow develops into a self-preserving flow further downstream (Rajaratnam 1976). The normalized velocity profile, $u/u_x$, will be universal and given as a function of $y/\delta$. $u_x$ is the maximum velocity at distance $x$, and $\delta$ is the $y$-directional at height to a velocity one-half of the maximum velocity, $u_x/2$ (Figure 2).

The velocity distribution in the vicinity of the floor is described by the decay of the maximum velocity, $u_x$, as a function of the distance $x$. The velocity decay is given by

$$\frac{u_x}{u_f} \sim \frac{h}{x + x_o} \tag{3}$$

in the case of a three-dimensional wall jet or a radial wall jet (Rajaratnam 1976).

In the case of a two-dimensional wall jet, it is given by

$$\frac{u_x}{u_f} \sim \sqrt{\frac{h}{x + x_o}} \tag{4}$$

where $h$ is the height of the diffuser. $x_o$ is the distance to a virtual origin for the self-preserving flow, as shown in Figure 2. This distance may either be positive or negative, but it is often a small distance compared to other distances in a room; it is, therefore, ignored in mixing ventilation.

The face velocity, $u_f$, is given as supply flow rate divided by the face area, $a_f$, of the diffuser for radial and three-dimensional flow, and it is given as supply flow rate divided by the total face area of all diffusers in two-dimensional flow.

The thickness, $\delta$, is proportional to the distance $x + x_o$ in all wall jet types assuming the flow is self-preserving.

$$\delta = D(x + x_o) \tag{5}$$

The growth rate, $D$, is a constant for each diffuser and has a value of 0.06 to 0.10 (Rajaratnam 1976).

## STRATIFIED FLOW

Stratified flow theory describes the flow from wall-mounted, low-velocity diffusers where the temperature differences are very large.

In water with a density current, the flow has those features shown in Figure 3. The flow close to the opening entrains water with low density, and the process is similar to the flow in a wall jet. There will be a roller region and a density jump at a certain distance. The entrainment will disappear in the flow further downstream from the density jump, especially, which is characteristic of stratified flow. The location of the density jump depends on the height of a weir located downstream in the flow (Wilkinson and Wood 1971). The density jump moves toward the opening if the weir is increased, resulting in decreasing entrainment into the density current. Further increase of weir height at this stage will cause the jump to flood, so that the upstream end of the jump becomes submerged in dense fluid. There is no entrainment into a flooded jump.

Stratified surroundings will damp the entrainment in a horizontal flow. The turbulence in the shear layer decreases because vertical movements in a fluid with a temperature gradient are damped by the buoyancy effect.

Entrainment, or lack of entrainment, is obviously an important parameter in stratified flow. Turner (1979) has shown that the rate of entrainment, $E$, can be given as a function of the overall Richardson number, $\mathrm{Ri}_x$, as shown in Figure 4. The entrainment function assumes that the entrainment into the horizontal flow is proportional to the local velocity, $U$. The Richardson number is defined as

$$\mathrm{Ri}_x = \frac{g \cdot \Delta\rho \, l}{\rho \cdot U^2} \tag{6}$$

where $g$ is gravitational acceleration, and $l$ and $U$ are characteristic length and characteristic velocity, respectively. $l$ and $U$ correspond to the height of the flow, $\delta$, and the maximum velocity, $u_x$, in the flow at location $x$ for the overall Richardson number. $\rho$ is the density of the heavy fluid, and $\Delta\rho$ is the local density increase. (In a two-layer system, the layer with the standard density, $\rho_o$, may be regarded as weightless, compared to the layer with density $\rho = \rho_o + \Delta\rho$. The heavy layer will flow as if it were influenced by a reduced gravitational acceleration $g\Delta\rho/\rho$ [Prandtl 1952]).

The most important feature shown in Figure 4 is the rapid fall of $E$ with increasing $\mathrm{Ri}_x$. The flow acts as a wall jet with entrainment if it is initiated with high velocity and low $\mathrm{Ri}_x$. The Richardson number increases downstream of the flow, and Figure 4 shows that the entrainment decreases and changes the flow to a stratified flow without entrainment. This process is shown in Figure 3, where entrainment takes place in the left side of the figure but disappears on the right side after the roller zone. Flow with high entrainment is called supercritical and moves to a subcritical state with increasing $\mathrm{Ri}_x$ as it passes the roller zone.

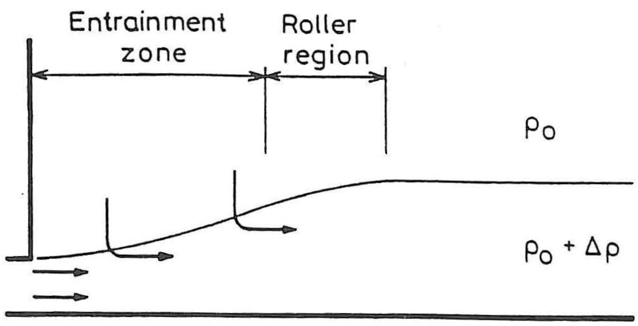


*Figure 3* *Stratified flow in water with both an entrainment zone and a zone with very little mixing between the two layers.*

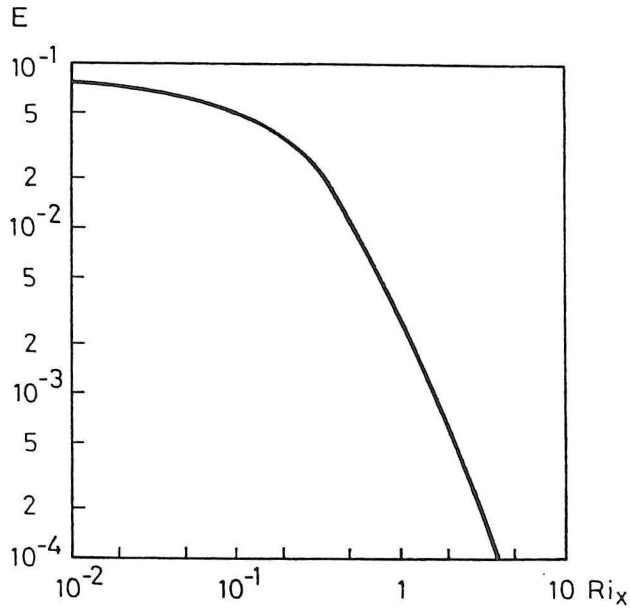


*Figure 4* *Rate of entrainment into a turbulent stratified flow as a function of overall Richardson number.*

The velocity distribution in a stratified radial flow with constant thickness, small entrainment, and universal velocity distribution is given by (Nielsen 1992):

$$u_x \sim \frac{1}{x} \tag{7}$$

The corresponding velocity distribution in a stratified, two-dimensional flow is given by

$$u_x \sim const. \tag{8}$$

The similar profiles measured in stratified flow in a room are often identical to the universal wall jet profile, and this paper therefore defines the length scale, $\delta$, as the height to the velocity $u_x/2$.

Profiles measured in hydraulics may also have a form different from a wall jet profile. Measurements by Lofquist (1960) show a profile with a high location of the maximum velocity. The high density $\rho_o + \Delta\rho$ is constant in the entire flow, except for a very thin layer with a gradient up to the $\rho_o$ layer. The density gradient in the flow is caused by different salt concentrations, and the problem cannot be compared to stratified flow in rooms where radiant heating of the floor plays an important role. Velocity profiles shown in the measurements of Wilkinson and Wood (1971) look more like a universal profile of a wall jet.

It is possible to show that the rate of entrainment, $E$, is proportional to the growth rate $D$, or

$$\frac{d\delta}{dx} \sim E. \tag{9}$$

The radial flow is described by Equation 3 in the supercritical stage and Equation 7 in the subcritical stage. The plane flow is described by Equation 4 in the supercritical stage and Equation 8 in the subcritical stage, as shown by Turner (1979) and Rodi (1982).

## VELOCITY DISTRIBUTION IN THE RADIAL FLOW FROM A WALL-MOUNTED DIFFUSER

The primary flow in a room with displacement ventilation expresses the similarity typical of fully turbulent flow. Vertical temperature gradients, velocity level in stratified flow at the floor, stratification level, and ventilation effectiveness can all be described by an Archimedes number independent of the velocity level in the room (Nielsen 1988). The Archimedes number is defined as

$$\mathrm{Ar} = \frac{\beta g h (T_{oc} - T_o)}{u_f^2} \tag{10}$$

where $\beta$, $g$, and $(T_{oc} - T_o)$ are volume expansion coefficient, gravitational acceleration, and temperature difference between the temperature at a height of 1.1 m and the supply temperature, respectively.

The flow from a wall-mounted diffuser is shown in Figure 5. The velocity ratio, $u_x/u_f$, is given as a function of the dimensionless distance, $x/h$. The cold air from the supply opening has a high initial acceleration due to gravity, and a relative velocity of 1.49 will be obtained some distance from the diffuser. ($u_x$ is the maximum velocity in the flow; it is located close to the floor (1 - 4 cm).

Figure 5 indicates that the maximum velocity in the symmetry plane is proportional to $1/x^{\alpha}$, where the exponent $\alpha$ is close to 1.0 (Nielsen et al. 1988). This type of velocity decay is typical of radial stratified flow (Equation 7).

The length scale or thickness $\delta$ is constant and independent of the distance from the diffuser at an Archimedes number of 5, as shown in Figure 6, which is a strong indication of stratified flow. The dotted line in the figure indicates a progress that could be expected in a wall jet (Equation 5).

The height of the flow region is much smaller than the height of the diffuser ($h$ = 0.56 m), even very close to the diffuser. This shows that cold air from the diffuser will reach the floor very close to the opening, at least within 0.5 m from the diffuser.

The maximum velocity $u_x$, at different distances, $x$, from the opening can be given by (Nielsen 1992):

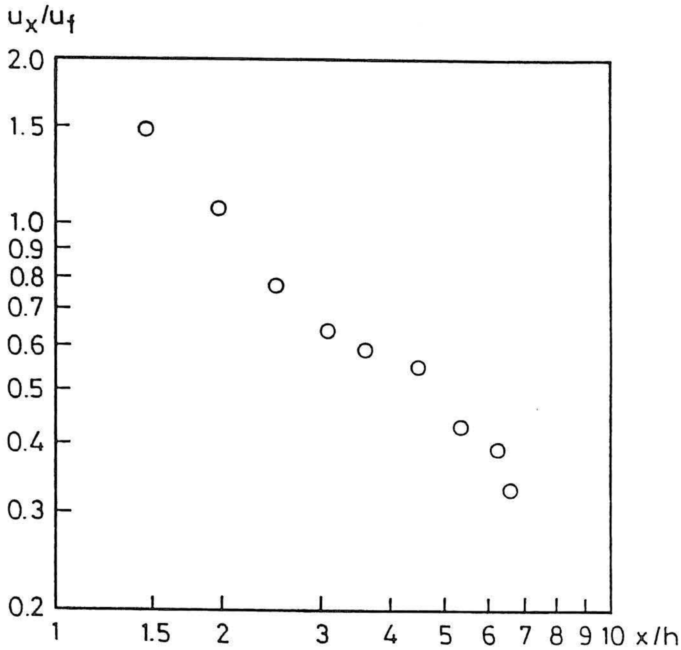


*Figure 5* *Maximum velocity close to the floor vs. distance from the diffuser. Diffuser type G. Ar = 7.4 and $q_o$ = 0.028 $m^3/s$.*

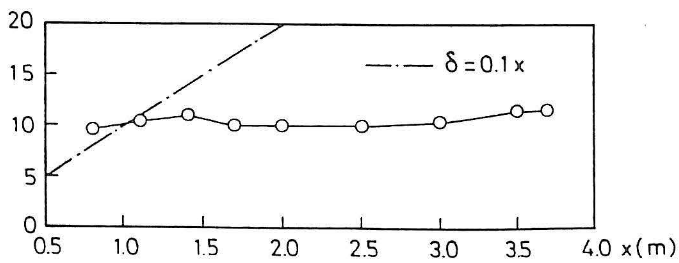


*Figure 6* *Length scale $\delta$ in the flow vs. distance from the diffuser. Diffuser type G. Ar ~ 5.*

$$\frac{u_x}{u_f} = K_{dr} \frac{h}{x} \tag{11}$$

where $h$ is the height of the diffuser, and $u_f$ is the face velocity defined as flow rate $q_o$ divided by the face area $a_f$ of the diffuser. $K_{dr}$ is a function of the Archimedes number as well as an individual function for different types of air terminal devices. Both $x$ and $u_x$ are measured at the center plane of the flow.

The equation is valid for small as well as large Archimedes numbers. In both cases, the velocity is proportional to $1/x$ (see Equations 2, 3, and 7), and the equation will therefore be able to predict the velocity $u_x$ when $K_{dr}$ is adjusted to the situation.

The variables in Equation 11 are easy to measure for a given diffuser, and the equation is therefore simple to use in a practical design procedure.

Figure 7 shows that $K_{dr}$ increases with increasing Archimedes number for the given diffuser (type G) because gravity accelerates the vertical flow close to the opening and generates a stratified air movement in a relatively thin layer along the floor. Increased Archimedes number decreases $\delta$ and increases the maximum velocity in the layer.

In stratified flow in hydraulics, obstacles located downstream influence the length scale, $\delta$, of the flow (Wilkinson and Wood 1971). The measurements in Figure 7 show that $K_{dr}$ is independent of the room length and the corresponding room width within the variation indicated in the figure. Practical experience also indicates that room dimensions are of minor importance (Nielsen 1992).

Here the entrainment process in the stratified flow will be discussed in greater detail. A local Archimedes number is defined by

$$\mathrm{Ar}_x = \frac{\beta g \delta \Delta T_x}{u_x^2} \tag{12}$$

where $\delta$, $u_x$, and $\Delta T_x = (T_{oc} - T_x)$ are all local reference values. $T_x$ is the minimum temperature in the flow, located close to maximum velocity $u_x$. It is assumed that the following expression can be used to estimate $\Delta T_x$ in case of high entrainment.

$$\frac{T_{oc} - T_x}{T_{oc} - T_o} \sim \frac{u_x}{u_f} . \tag{13}$$

The length scale $\delta$ is proportional to $x$ in the supercritical stage, and $\Delta T_x$ is proportional to $1/x$ (Equations 11 and 13). $u_x^2$ is proportional to $1/x^2$. The total effect is that $\mathrm{Ar}_x$ is proportional to $x^2$ in the supercritical stage; it will, therefore, increase with distance $x$. It is also possible that the local Archimedes number will increase with distance $x$ in the subcritical stage due to decreasing velocity.

The rate of entrainment, $E$, is measured at different positions in the flow, and Figure 8 shows a variation similar to the result indicated in Figure 4. The stratified flow moves from a supercritical stage to a subcritical stage with an abrupt decrement of the entrainment rate. Jacobsen and Nielsen (1992) have shown a similar variation of the entrainment function.

Sandberg and Mattsson (1991) suggest that the flow field in front of the diffuser should be divided into super- and subcritical flow domains.

## VELOCITY DISTRIBUTION IN PLANE FLOW FROM WALL-MOUNTED DIFFUSERS

The flow from a number of diffusers placed close to each other on the wall merges to a two-dimensional stratified flow in the downstream direction. The same effect

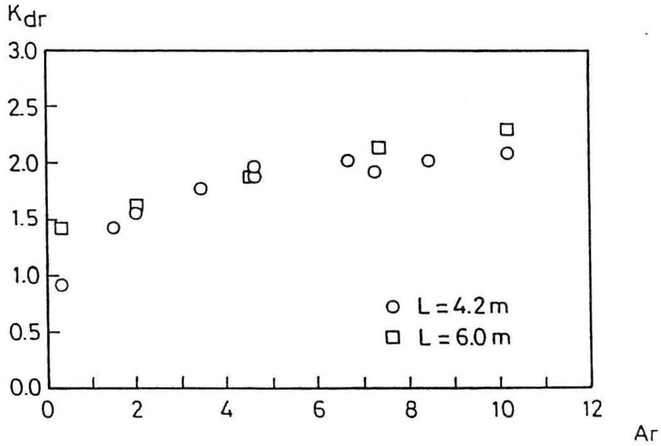


*Figure 7* $K_{dr}$ *measured in the middle plane vs. Archimedes number for a wall-mounted air terminal device (type G).*

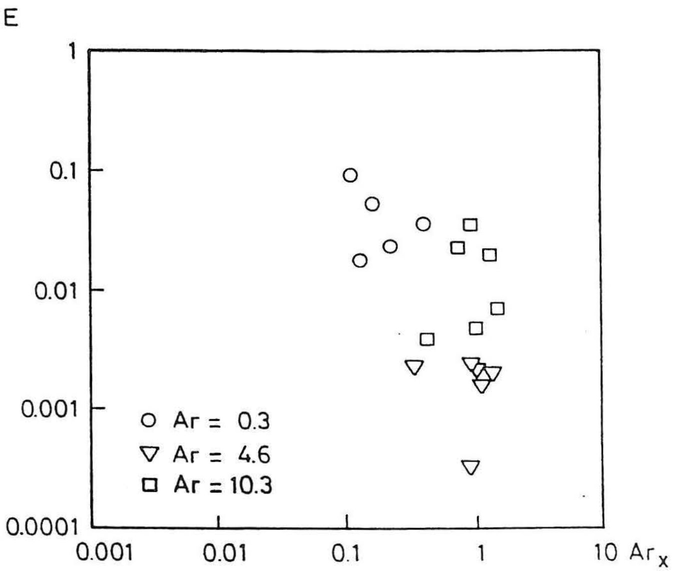


*Figure 8* *Rate of entrainment vs. the local Archimedes number* $Ar_x$ *for diffuser type G.*

occurs when the room is larger in the $x$-direction than in the width.

Figure 9 shows some measurements of the flow. There is a high velocity decay for $x < 1.5$ m due to a radial flow from the diffusers. The flow merges into a two-dimensional air movement for $x > 1.5$ m, but there is still some velocity decay. The velocity level seems to be strongly dependent on the flow rate.

The relative velocity level, $u_x/u_f$, is shown in Figure 10 for the same set of measurements as shown in Figure 9. The velocity level is slightly influenced by the Archimedes number, with an increase of the velocity level at increasing Archimedes number. The velocity, $u_x$, is proportional to the face velocity, $u_f$, or the flow rate, $q_o$, at a given distance, $x$. The measurements are made in a room with three type $E$ diffusers distributed over a width of 3.6 m. $q_o$ is the total flow rate to the room, and $h$ is the equivalent height of a two-dimensional diffuser covering the entire width of the room. The Archimedes number in this section is consequently based on this definition.

The figure indicates that the velocity decay is proportional to $1/x^{0.5}$ in certain areas. This is also the velocity decay that should be expected in wall jet flow (Equation 4), but it might also be the transition from radial flow to stratified plane flow. It is possible to observe some areas with a constant velocity level typical of a stratified plane flow, as shown in Equation 8.

The plane stratified flow may be described by

$$\frac{u_x}{u_f} = K_{dp} \tag{14}$$

where $K_{dp}$ is equal to 1.1 for Ar= 3 and equal to 1.4 for Ar = 29. $K_{dp}$ is a function of the diffusers and the geometry around the diffusers as well as the Archimedes number. Equation 14 only describes the flow in a narrow range of distances, as shown by the measurement in Figure 10.

The plane flow can be further analyzed from measurements of the length scale, $\delta$. Figure 11 shows that the length scale has an initial increase similar to the growth of a wall jet; this is the type of flow that can be found in the supercritical stage. The flow will change from increasing $\delta$ to constant $\delta$ downstream in the air movement at all three Archimedes numbers, which is typical of stratified flow.

It was not possible to predict the entrainment function, $E$, but Equation 9 shows that constant length scale $\delta$ is equivalent to zero entrainment.

Figure 11 shows that increasing Archimedes number gives decreasing thickness, $\delta$. This effect may explain the increase in relative velocity $u_x/u_f$ in case of a large Archimedes number as discussed in connection with Figure 10.

The heat load per diffuser is reduced when more diffusers are used in a room. It is therefore possible to reduce the velocity level close to the diffusers when more diffusers are used. It is also possible to obtain two-dimensional flow with a velocity in the main part of the occupied zone that is lower than the velocity close to a single diffuser producing a radial flow.

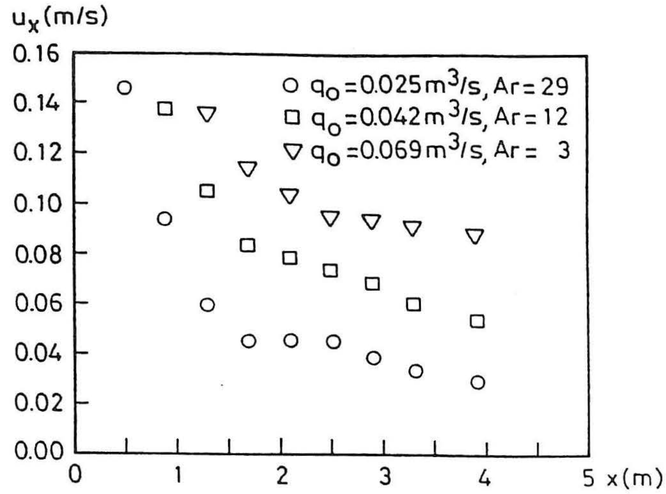


*Figure 9* *Maximum velocity* $u_x$ *vs. distance* $x$ *from the end wall at three different flow rates and three different Archimedes numbers. Plane flow.*

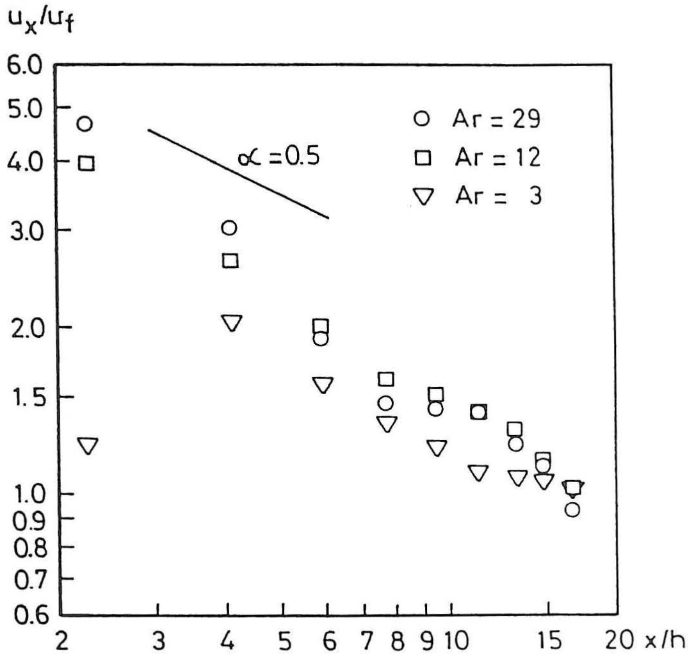


*Figure 10* *Relative velocity* $u_x/u_f$ *vs. relative distance* $x/h$ *for three different Archimedes numbers. Plane flow.*

## CONCLUSION

Isothermal wall jets and stratified flow theory are discussed in general.

The velocity level in the occupied zone can be described by a single equation based on stratified flow theory and measurements.

A two-dimensional stratified flow is obtained if the room is ventilated by a number of diffusers placed close to each other on a single wall. The velocity level in a room

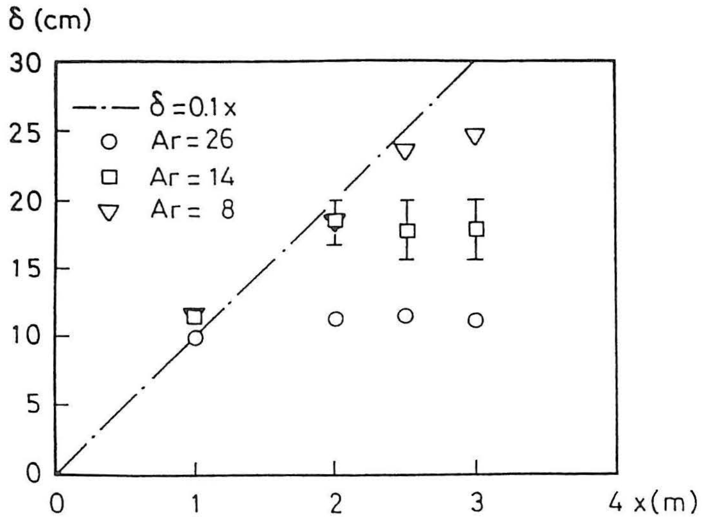


***Figure 11*** *Length scale variation in plane flow at three different Archimedes numbers.*

with two-dimensional flow may be lower than the velocity in the vicinity of a single diffuser at a given heat load.

It is necessary to make more measurements in two-dimensional flow to obtain a complete description of the general air movement, but it is shown that the velocity will be constant in an area in front of the diffusers in the case of stratified flow.

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## DISCUSSION

**James T. Reardon, Research Officer, Institute for Research in Construction, National Research Council, Ottawa, ON, Canada:** Thank you for a very interesting presentation. It suggests that analytical predictions backed by experiment are useful for understanding and characterizing room airflows.

Were CFD simulations conducted in parallel with these experiments and predictions? If so, which approach (CFD vs. analytical/experimental) offers the most effective means (practically and idealistically) to examine airflows in idealized empty rooms and realistic furnished rooms? (Thus far, the CFD efforts have not ventured into realistic furnished cases, have they?)

**P.V. Nielsen:** CFD simulations were also conducted in parallel with the experiments. I think that the experimental method offers the most effective means to examine the airflow. The reason is that stratification flow in empty and furnished rooms is a new research area for CFD, and CFD simulations therefore have to be tested against some experiments. CFD simulations of stratified flow are giving promising results (see Jacobsen and Nielsen, "Numerical Modelling of Thermal Environment in a Displacement-Ventilated Room," presented at Indoor Air '93 in Helsinki).

CFD simulation of jet flow and mixing ventilation is a useful tool today. This can be shown, for instance, by the papers in *Building Systems: Room Air and Air Contaminant Distribution* (ASHRAE 1989).

PAPER NO. 51: Peter V. Nielsen: *Healthy Buildings and Air Distribution in Rooms.* ISSN 1395-7953 R9538.

PAPER NO. 52: Lars Davidson & Peter V. Nielsen: *Calculation of the Two-Dimensional Airflow in Facial Regions and Nasal Cavity using an Unstructured Finite Volume Solver.* ISSN 1395-7953 R9539.

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PAPER NO. 59: L. Davidson & P. V. Nielsen: *Large Eddy Simulations of the Flow in a Three-Dimensional Ventilated Room.* ISSN 1395-7953 R9651.

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